EVALUATION OF ANALYTICAL INDUSTRIES INC. MODEL NUMBER PSR-11-33-NM OXYGEN SENSORS FOR USE WITH THE MK 16 MOD 1 UNDERWATER BREATHING APPARATUS

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Navy Experimental Diving Unit

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The Navy Experimental Diving Unit (NEDU) conducted unmanned and manned evaluation of the Analytical Industries Inc. oxygen sensor (PSR-11) with the MK 16 MOD 1 UBA, as stand-alone sensors and in combination with Teledyne Analytical Industries R-10DN oxygen sensor. Currently only the Teledyne R-10DN sensor is approved for use with the MK 16 MOD 1 UBA. Another approved sensor would mitigate the potential impact if the current sensor is unavailable or is suspended from use for any reason. Tests were conducted through a full range of operation limits, from the unmanned laboratory to open ocean manned diving. The PSR-11 sensor performed adequately in all scenarios. The PSR-11 sensor is recommended for fleet usage with the MK 16 MOD 1 UBA.

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INTRODUCTION

The purpose of this study was to conduct unmanned and manned testing to evaluate the effectiveness of the Analytical Industries' PSR-11 oxygen sensor (alone and in combination with approved Teledyne R-10DN oxygen sensors) with the MK 16 MOD 1 underwater breathing apparatus (UBA) to a maximum excursion depth of 300 feet of seawater (fsw).[1] Primarily employed by Navy Explosive Ordnance Disposal (EOD) divers, the MK 16 MOD 1 UBA is an electronically controlled, closed-circuit, mixed gas, constant oxygen partial pressure (PO_2) underwater life-support system that meets military specifications for nonmagnetic and acoustically safe equipment. This system employs three sensors to monitor the oxygen concentration in its breathing loop.

Currently only one oxygen sensor, the Teledyne R-10DN, is approved for use with the MK 16 MOD 1 UBA. Having another sensor approved could mitigate potential operational problems if the current sensor is unavailable or its use is suspended for any reason. The PSR-11 was therefore a candidate for consideration as an approved, compatible substitute for the Teledyne R-10DN sensor.

UNMANNED EVALUATION

METHODS

GENERAL

Unmanned testing of the PSR-11 sensors was conducted in the Experimental Diving Facility (EDF) at Navy Experimental Diving Unit (NEDU), to evaluate their ability to function in the MK 16 MOD 1 UBA alone and in combination with R-10DN sensors to the maximum excursion depth of 300 fsw (91.9 meters of seawater [msw]).

EXPERIMENTAL DESIGN AND ANALYSIS

All unmanned testing was conducted per NEDU Technical Manual No. 01-94,[2] with the following exceptions:

> Each MK 16 MOD 1 UBA was tested at one respiratory minute volume (RMV) rate and with two different diluents: 79/21 N_2O_2 to a maximum depth of 190 fsw (58.2 msw), and 88/12 HeO_2 to a maximum depth of 300 fsw. One UBA was assembled with three PSR-11 sensors, a second with two PSR-11 sensors and one R-10DN sensor, and third with one PSR-11 sensor and two R-10DN sensors. By measuring the output from each sensor and the electrical output of the MK 16 primary electronic assembly that regulates the oxygen addition valve, we recorded and evaluated sensor readings and oxygen addition valve opening times throughout the dive. Water temperatures during testing were $29.0 \pm 2.0\ °F$ ($-1.7 \pm 1.1\ °C$) and $104.0 \pm 2.0\ °F$ ($40.0 \pm 1.1\ °C$). Water depth was recorded throughout the dive.

The task leader reduced the data acquired in this unmanned testing phase, analyzed the degree of error between all sensors to determine the effectiveness of the PSR-11, and compared opening times of the oxygen addition valves for the different sensor combinations. The task leader or assigned representatives were present during the setup and postdive procedures for all UBAs tested.

EQUIPMENT AND INSTRUMENTATION

The following personnel and logistical support were required for testing: six PSR-11 sensors, three R-10DN sensors, three MK 16 MOD 1 UBAs, and the EDF manned with a complete watch section. Because of differences in test depths, each UBA was tested with two different diluent mixes and at two different temperatures. The EDF Bravo chamber was pressurized to the maximum depth of 190 fsw for N_2O_2 and 300 fsw for HeO_2 at a descent rate of 60 ± 3 feet per minute (ft/min). The ascent rate was 30 ± 3 ft/min. All oxygen sensors and the oxygen addition valve were monitored throughout the dive.

NOTE: After the depth was changed and before testing began, the parameters property sheet in the breathing machine software was properly updated.

a. Temperatures: cold water: 29.0 ± 2.0 °F
                        warm water: 104.0 ± 2.0 °F

b. Diluent gases: 79/21 N_2O_2 190 fsw
                     88/12 HeO_2 300 fsw

c.

Breathing Rate	/	Tidal Volume	/	RMV
25 BPM	/	2.5 liters	/	62.5 liters/minute

BPM = breaths per minute

d. EDF Bravo chamber

e. Insulated rectangular water container (ark; 700-gallon capacity) capable of 29–104 °F temperature range

f. UBA mounted in a vertical position

g. Mechanical breathing simulator (Reimers dual piston, variable volume 0–5 L and frequency to 60 cycles per minute), calibrated volume stops at 2.5 L; calibrated frequency stop at 25 BPM, sinusoidal waveform

h. Pentium 2 gigahertz Windows XP personal computer system with National Instruments LabVIEW data acquisition software and NEDU-developed software for processing data

i. Druck, Inc., oral/nasal differential pressure transducer (±1 pound per square inch differential [psid; 6.9 kilopascals {kPa}]), model PTX317-9219

j. Matheson mass flow controller, model number 8280

k. NEDU-developed MK 16 MOD 1 interface / data acquisition unit

l. Three MK 16 MOD 1 UBAs

m. Six PSR-11 and three R-10DN oxygen sensors

PROCEDURES

Initial setups and predives of UBAs were conducted per the *U.S. Navy Diving Manual*.[3] The candidate UBA-installed gas cylinders provided the gas supplies. Only carbon dioxide (CO_2) absorbent authorized by Naval Sea Systems Command was used.[4]

UBAs were configured with the required O_2 sensors and connected to the chamber breathing machine. Sensor readings to the computer were verified, and the UBAs were flushed with 100% oxygen. The mechanical breathing simulator was started, and the UBAs were allowed to stabilize before the dive profile was conducted, per the test parameters.

In 29 °F water, expired gas was humidified (saturated at 98 °F [36.7 °C]) and maintained at a temperature of 82 ± 10 °F (27.8 ± 5.6 °C) at the routing gas "T." In 104 °F water, the expired gas was also humidified, but no attempt was made to control its temperature. Carbon dioxide then was injected into the breathing loop at a rate of 2.5 liters per minute.

For each sensor/UBA configuration, two dives were made to the maximum depth (190 fsw for N_2O_2; 300 fsw for HeO_2). In both cases, the UBAs remained submerged on the surface until their oxygen partial pressures (PO_2) had stabilized. All dives made stops at 40 fsw (12.2 msw), at the midway point, at 100 fsw (30.6 msw), at 150 fsw (45.9 msw), and at the bottom. On ascent, stops were made at the midway point and at 10 fsw (3.06 msw). After the ark temperature had been reset, dives were repeated. A total of twelve dives, six at each temperature setting, were completed.

Pearson correlation tests were used to obtain correlations between readings with each type of sensor. Univariate Analysis of Variance (ANOVA) was used to compare the two sensor types.

RESULTS

Recordings from all combinations of diluent gas and temperatures were obtained from MK16s with one PSR-11 sensor and two R-10DN sensors. In tests with two PSR-11 sensors and one R-10DN sensor, recordings were obtained at both temperatures with HeO_2 as diluent and at 104 °F with air as diluent. In tests with three PSR-11 sensors, recordings were made with air as diluent at both temperatures and with HeO_2 as the diluent at 104 °F. Data are presented in Table 1.

DISCUSSION

The tests with three PSR-11 sensors showed that the readings were highly correlated (Pearson's r>0.94, n = 40): i.e., the ANOVA showed that the PSR-11 sensors did not statistically differ from each other, nor did the R-10DN sensors statistically differ at either PO_2 set point (F = 0.429; p = 0.88). There was also no difference between the PSR-11 and the R-10DN sensors at both PO_2 set points.

The PSR-11 and R-10DN sensors show no difference in performance.

Table 1.
Means and standard deviations from the oxygen sensors under the different conditions

Temperature (°F)	Diluent gas	Sensor type	PO_2 set point	mean	SD
29	Air	PSR-11	0.75	0.721	0.012
			1.3	1.254	0.045
		R-10DN	0.75	0.698	0.010
			1.3	1.212	0.010
	Heliox (HeO_2)	PSR-11	0.75	0.738	0.025
			1.3	1.263	0.054
		R-10DN	0.75	0.708	0.026
			1.3	1.232	0.060
104	Air	PSR-11	0.75	0.793	0.075
			1.3	1.362	0.108
		R-10DN	0.75	0.747	0.066
			1.3	1.305	0.083
	Heliox	PSR-11	0.75	0.793	0.048
			1.3	1.376	0.143
		R-10DN	0.75	0.768	0.058
			1.3	1.375	0.175

MANNED EVALUATION

METHODS

GENERAL

Manned testing was conducted in three phases: Phase I, familiarizing dives with the equipment in the test pool; Phase II, diving in the OSF to the maximum working depths for each gas mix; Phase III, open water diving to depths of 185 fsw. The following personnel and logistical support were required:

Phase I: Two KMS 48 full face masks (FFMs), four MK 16 MOD 1 UBAs (two with PSR-11 sensors, one with a single PSR-11 sensor and two R-10DN sensors, and one with two PSR-11 sensors and one R-10DN), one safety diver in scuba, ten MK 16 MOD 1 divers, and a manned dive station on the test pool.

Phase II: Four KMS 48 FFMs, six MK 16 MOD 1 UBAs (two with PSR-11 sensors, one with one PSR-11 sensor and two R-10DN sensors, one with two PSR-11 sensors and one R-10DN, and two with R-10DN sensors for emergency breathing systems [EBS]), and the OSF manned for diving two teams of four divers daily.

Phase III: Two KMS 48 FFMs, four MK 16 MOD 1 UBAs (two with PSR-11 sensors, one with one PSR-11 sensor and two R-10DN sensors, and one with two PSR-11 sensors and one R-10DN), one dive boat outfitted with dive station load-out for open ocean diving with two divers, and a qualified MK 16 diving supervisor on station.

EXPERIMENTAL DESIGN AND ANALYSIS

The purpose of this manned testing was to evaluate the PSR-11 as a stand-alone oxygen sensor and to evaluate its sensor compatibility with the R-10DN during manned dives with the MK 16 MOD 1 to that UBA's maximum working depths. If a sensor performs effectively, the UBA must stabilize PO_2 within anticipated operating ranges for the MK 16 MOD 1.

EQUIPMENT AND INSTRUMENTATION

UBA O_2 Sensor Calibration

Before the start of Phase I dives, the voltage outputs of all R-10DN and PSR-11 sensors to be used in the MK 16 MOD 1 UBAs were measured in the laboratory at a series of PO_2 values from 0.21 to 2.10 atmospheres (atm), as the sensors were compressed in air. This procedure was repeated after Phase III dives were completed. Data were used to establish sensor stability throughout the man-dives and to correct PO_2 values for sensor nonlinearity that were recorded from UBA secondary displays.

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Before each day's diving, each MK 16 MOD 1 was calibrated in accordance with the *U.S. Navy Diving Manual.*[3] The following equipment was used during testing:

a. Four KMS 48 FFMs

b. Six MK 16 MOD 1 UBAs

c. MK 23 oxygen transfer pump apparatus (OTPA) / high-pressure charging station

d. EBS frame and communication cable

e. Off-the-shelf MK 7 / two-diver communication system

f. HeO_2 (88/12) for 300 fsw and N_2O_2 (79/21) for 190 fsw no-decompression dive

g. Dive boat, with complete dive station load-out

h. Hand-held sonar, acoustic beacon, and targets

During Phase II only, the inhalation hose of each MK 16 MOD 1 was fitted with a gas sampling block at the hose's juncture with the scrubber assembly.

PROCEDURES

Divers using safe diving practices[3] conducted manned evaluation of the PSR-11 with the MK 16 MOD 1.

Phase I Testing: During this phase, divers were familiarized with form, fit, and function of the KMS 48, the EBS, and the test procedures in the NEDU test pool.

Phase II Testing: Divers using EBS equipment and the MK 16 MOD 1 UBA outfitted with the PSR-11 and the R-10DN sensors were conducted in the NEDU OSF. Dives were conducted to 190 fsw with N_2O_2 (79/21) as the diluent and to 300 fsw with HeO_2 (88/12) as the diluent.

Phase III Testing: The diving was conducted in open water, open ocean. A series of open water dives simulating a mine countermeasure diving operation was conducted over a four-day period.

RESULTS

Phase II

Oxygen Fuel Cell Monitoring

Each diver's inspired O_2 partial pressure was monitored with a Teledyne R-10DS oxygen fuel cell in the gas sample block at the base of each MK 16 MOD 1 inhalation hose. Voltage output from each fuel cell was passed by umbilical to a real-time data acquisition system on the OSF Medical Deck, where it was converted to PO_2 in atmospheres and recorded at two-second intervals. In postdive analyses, Dr. Wayne Gerth's methods[5] were used to correct recorded PO_2 values for nonlinearities in fuel cell output versus PO_2. For these corrections, fuel cell voltage outputs measured in the laboratory were used before and after the dive series, as each cell was compressed in air to produce PO_2 values ranging from 0.21 to 2.10 atm. Only small degradations in fuel cell performance, degradations graphically manifested as slight increases in curvature of the voltage output versus the PO_2 curves for each cell, were found to have occurred during the dives. These degradations were neglected, and both preseries and postseries data for each cell were combined. Corrections were then made with a quadratic equation fitted to the data for each cell.[5] Preseries, postseries, and fitted laboratory calibration lines for each of the four fuel cells in this study are shown in Appendix B, along with the values of the coefficients of the quadratic equation fitted to the combined data for each cell.

Table 2 presents information about diver-inspired PO_2 during each profile, information compiled from the corrected profiles with software developed in earlier work.[6] Corrected dive profiles are shown in Appendix A.

Phase III

During Phase III we accomplished four days of open ocean diving. These dives had open water transits of up to nine miles one way to the dive site in a 24-foot, rigid hull inflatable boat (RHIB). We conducted 30 dives between 40 fsw and 185 fsw, with only one sensor failure over the four days of diving. All other sensors performed up to normal operating standards.

Table 2.
Dive-by-Dive MK 16 MOD 1 PO$_2$ Control Summaries

Profile	Dive Depth (fsw)	DESCENT RATE (fsw/min)	BOTTOM Time (min)	Total Dive Time (min)	PO$_2$ Overshoot Data			Pst OS TWA PO$_2$ (atm)	BT TWA PO$_2$ (atm)	Dive TWA PO$_2$ (atm)
					PO$_2$ MAX (atm)	Time PO$_2$>1.45 (min)	TWA PO$_2$ (atm)			
N$_2$O$_2$										
031202BLU1	190.9	60.3	7.73	14.63	2.612	6.433	2.081	0	1.908	1.663
031202BLU2	190.9	59.5	7.80	14.53	1.891	6.067	1.761	0	1.606	1.431
031202BLU3	190.7	57.6	7.67	14.70	1.551	2.567	1.502	1.404	1.321	1.223
031202GRN1	190.9	59.9	7.67	14.67	1.971	6.033	1.829	0	1.674	1.467
031202GRN2	190.9	59.7	7.80	14.53	1.905	6.100	1.789	0	1.632	1.432
031202GRN3	190.8	60.9	7.73	14.70	1.943	6.133	1.819	0	1.672	1.450
031202RED1	190.9	59.9	7.73	14.67	2.023	5.833	1.918	0	1.711	1.386
031202YEL1	190.9	60.3	7.73	14.63	2.139	6.300	1.912	0	1.757	1.520
031202YEL2	190.9	59.6	7.80	14.53	2.086	6.533	1.902	0	1.773	1.555
031202YEL3	190.7	57.6	7.67	14.70	1.954	6.100	1.823	0	1.672	1.463
HeO$_2$										
031204BLU1	301.6	57.6	7.77	37.00	2.013	5.733	1.814	0	1.631	1.337
031204BLU2	301.4	59.0	7.77	36.43	2.026	5.767	1.843	0	1.644	1.365
031204GRN1	301.7	55.9	7.77	37.00	1.787	6.167	1.655	0	1.533	1.355
031204GRN2	301.4	58.7	7.77	36.46	1.882	3.667	1.174	1.147	1.147	1.079
031204RED1	301.7	55.9	7.77	37.00	1.843	5.233	1.670	0	1.460	1.350
031204RED2	301.4	59.2	7.77	36.46	1.925	5.733	1.781	0	1.598	1.426
031204YEL1	301.6	57.7	7.77	37.06	2.019	5.533	1.832	0	1.618	1.425
031204YEL2	301.4	59.1	7.70	36.43	2.058	5.867	1.865	0	1.680	1.417

Note: TWA-Time Waited Average; Pst OS-Post Overshoot; BT- Bottom Time

CONCLUSIONS

The mean average reading for all sensors reaching the bottom of the HeO$_2$ 300 fsw dives equaled PO$_2$ of 1.79. This, one of the worst-case dives for the MK 16 MOD 1, is a good demonstration of UBA oxygen control. During unmanned and manned testing the Analytical Industries PSR-11-33-NM oxygen sensors proved to be compatible with and equal to the Teledyne R-10DN oxygen sensor used in the MK 16 MOD 1 UBA.
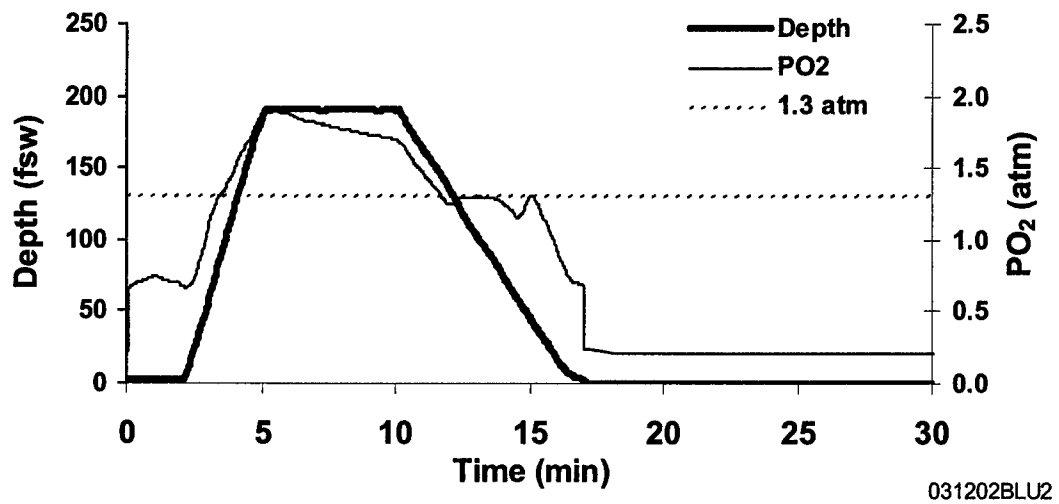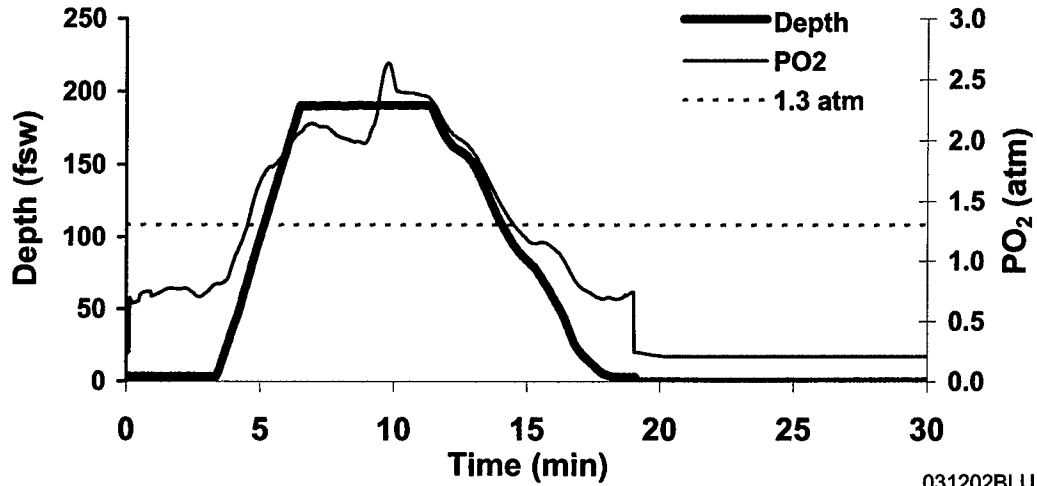
RECOMMENDATION

Following the completion of Phase III testing of the PSR-11 oxygen sensor, NEDU LTR Ser 033/010, dated 28 Jan 04, revealed that the equipment performed adequately. NEDU recommends that this sensor be approved for use in the MK 16 MOD 1, both in combination with the Teledyne R-10DN and in stand-alone configurations.
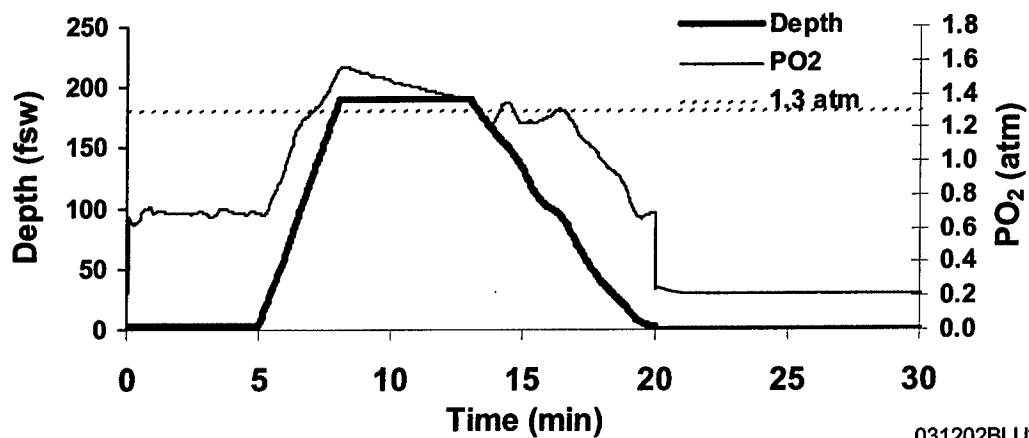
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3. Commander, U.S. Naval Sea Systems Command, *U.S. Navy Diving Manual, Revision 4*, Publication SS521-AG-PRO-010 (Arlington, VA: NAVSEA, 1999), Ch. 17.

4. Commander, U.S. Naval Sea Systems Command, *MK 16 MOD 1 Operation and Maintenance Manual*, 0910-LP-002 (Arlington, VA: NAVSEA, 2002).

5. W. A. Gerth, K. A. Gault, and S. J. Stanek, NEDU TR 03-14, *Empirical Evaluation of the MK 16 MOD 1 UBA Breathe-Down Procedure*, Navy Experimental Diving Unit, July 2003.

6. W. A. Gerth and T. M. Johnson, NEDU TR 02-10, *Development and Validation of 1.3 ATA PO$_2$-in-He Decompression Tables for the MK 16 MOD 1 UBA*, Navy Experimental Diving Unit, Aug 2002.

N$_2$O$_2$ Dives

031202BLU1

031202BLU2

031202BLU3

031202GRN1

031202GRN2

A2

031202GRN3

031202RED1

031202YEL1

A3

031202YEL2

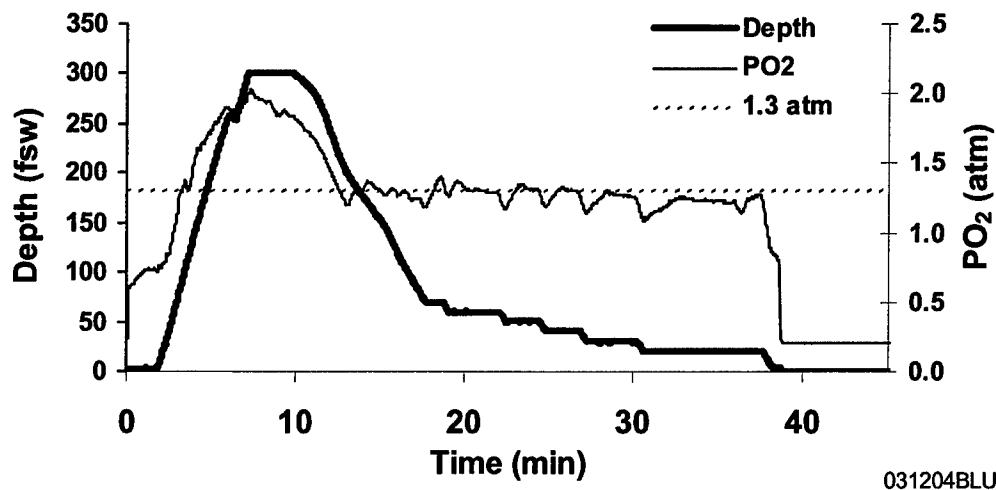031202YEL3

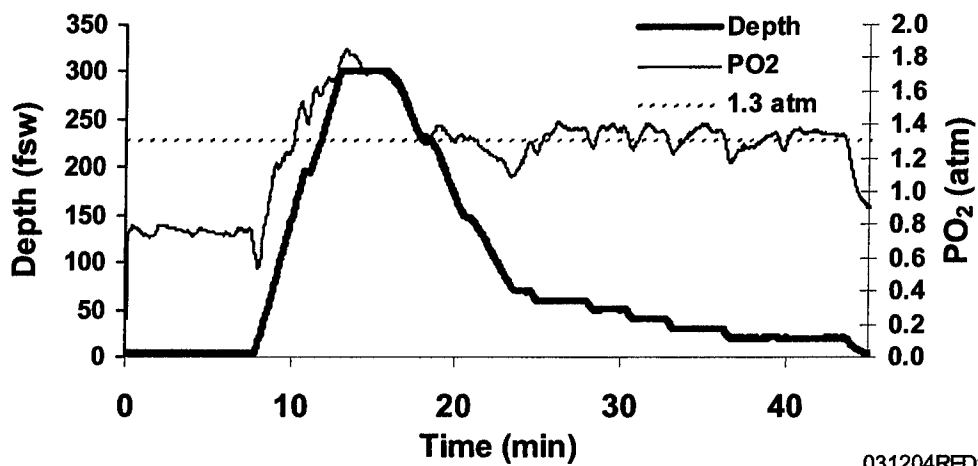**HeO₂ Dives**

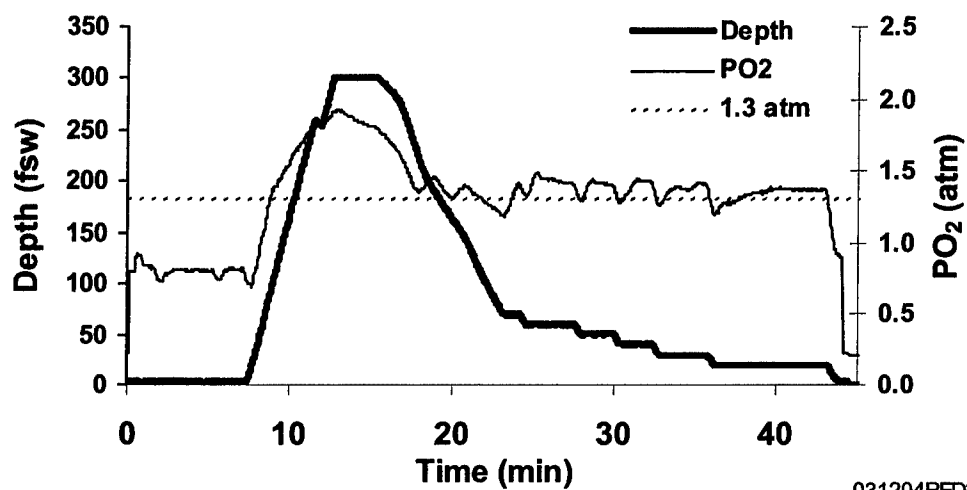031204BLU1

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031204BLU2

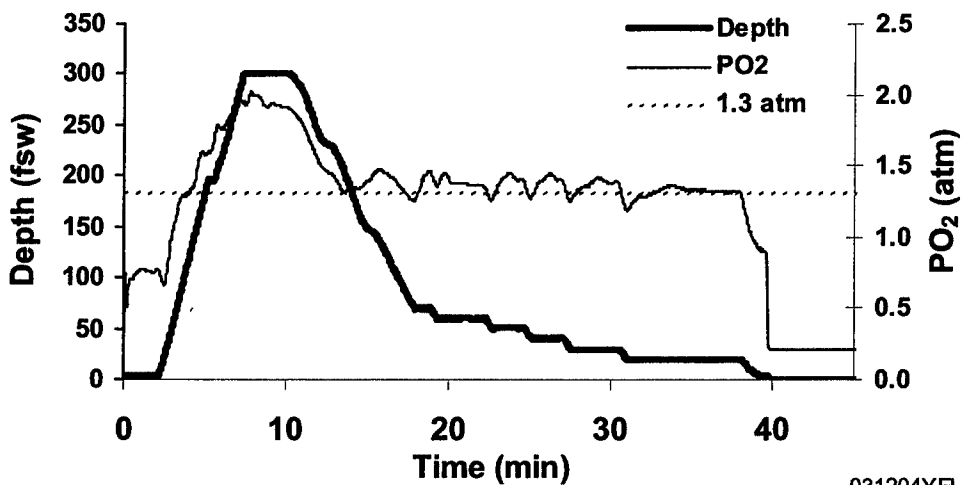031204GRN1

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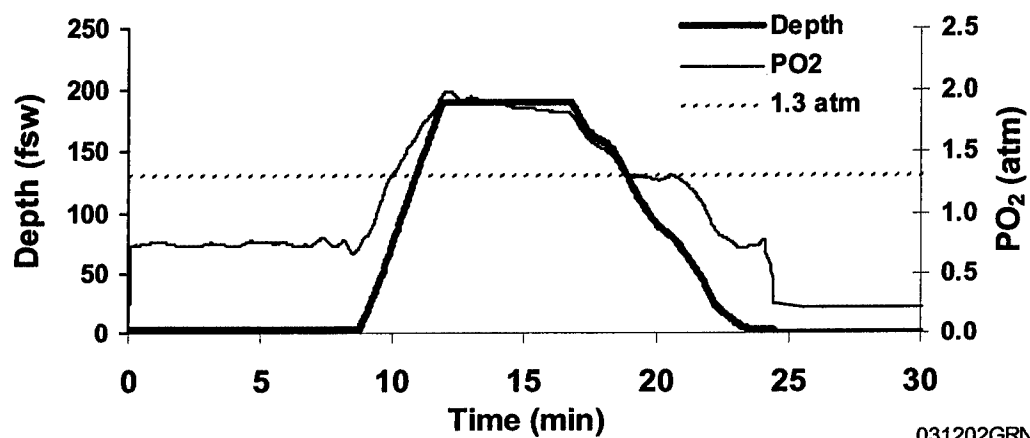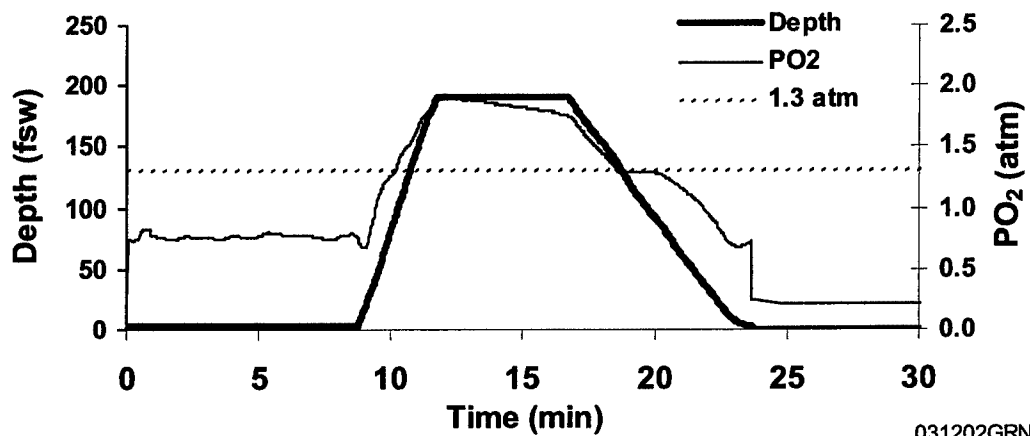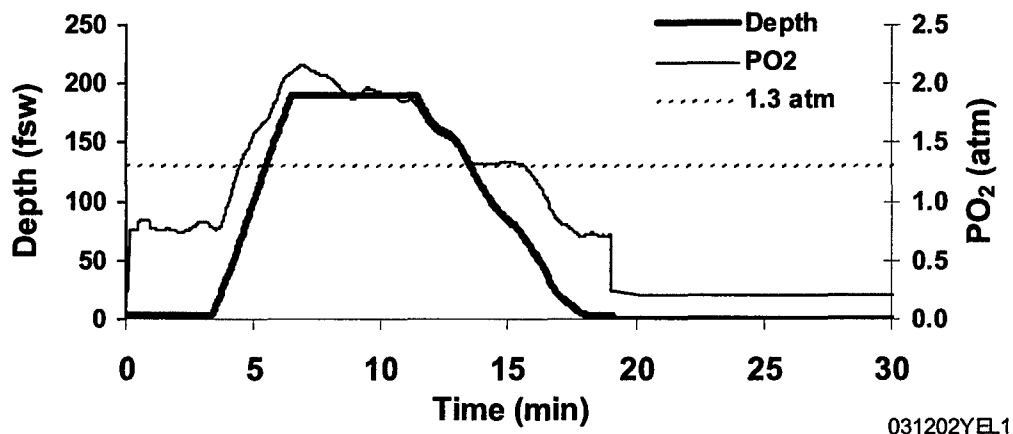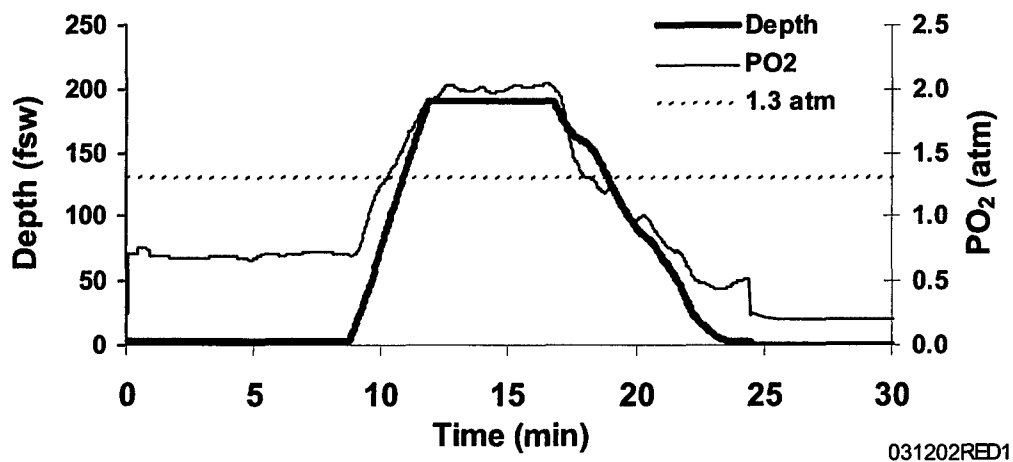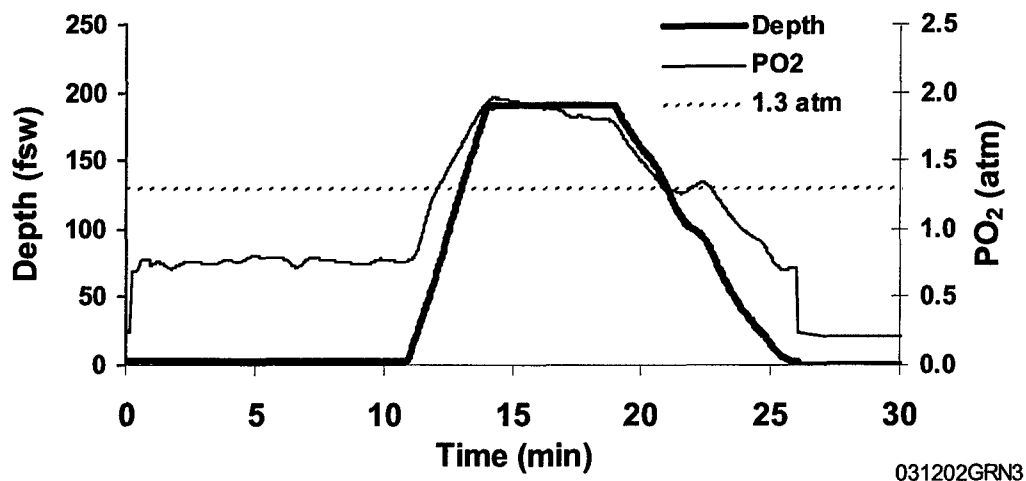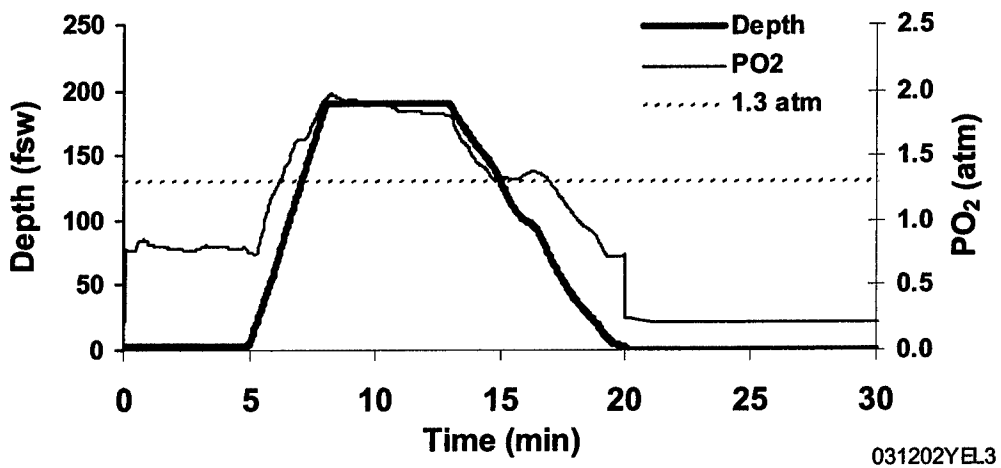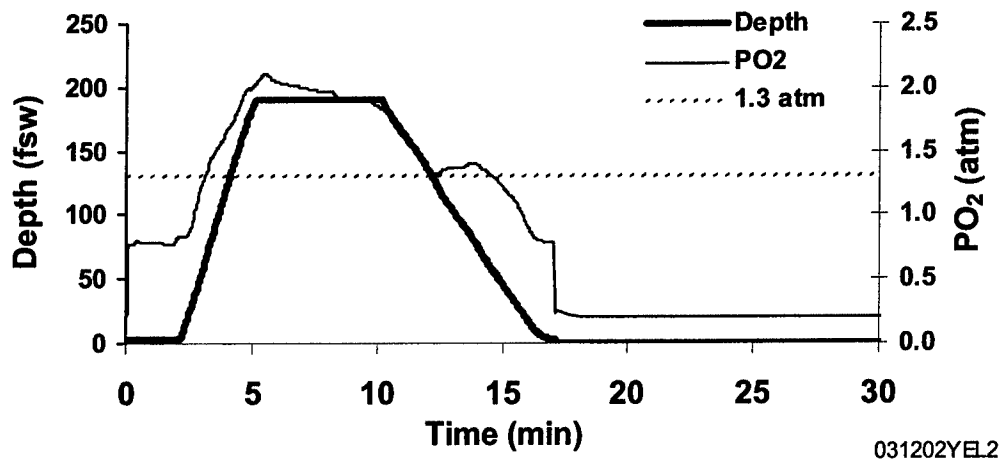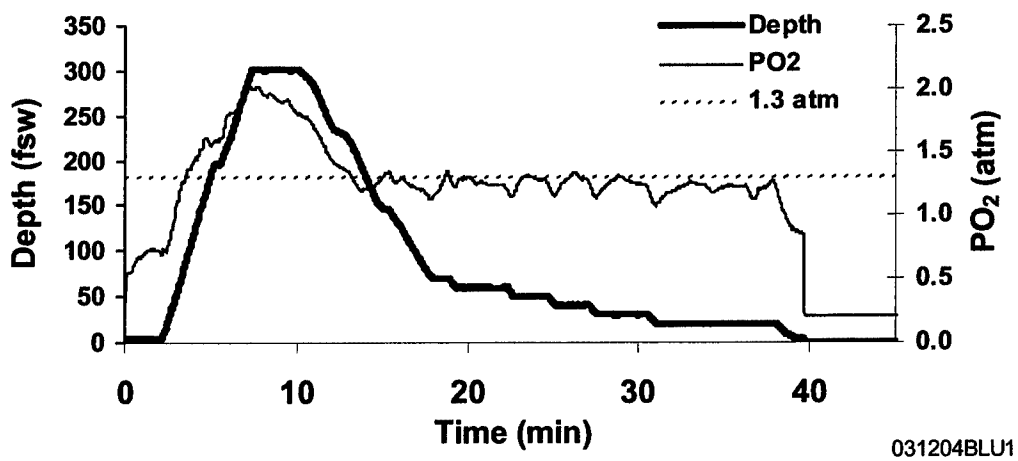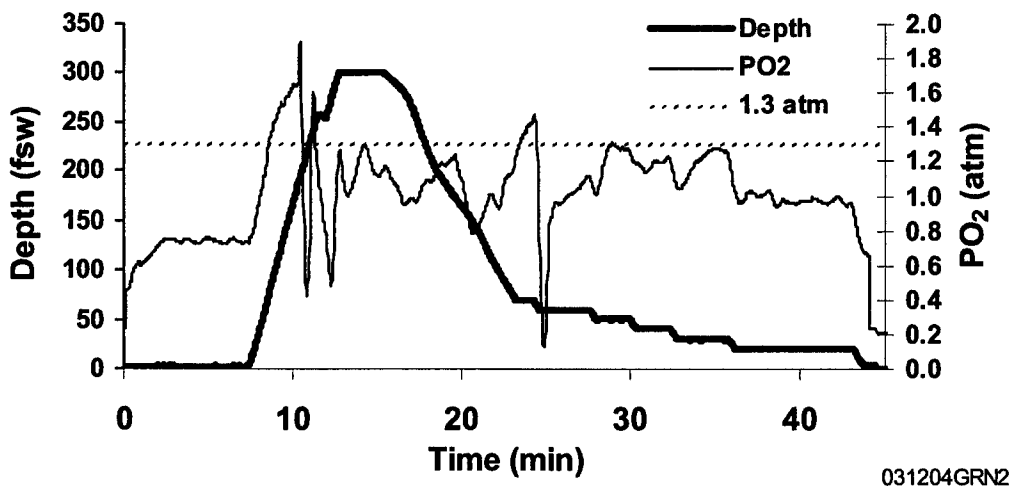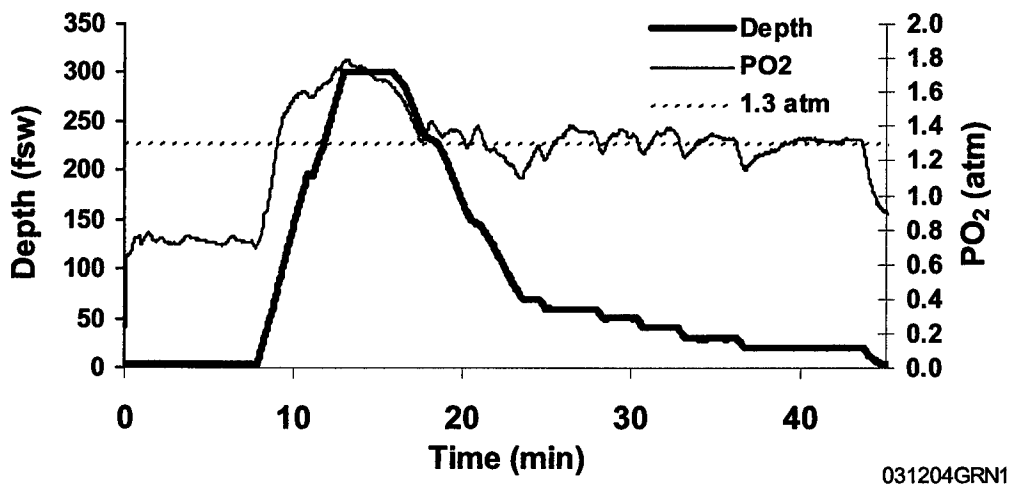
Note: Green diver's MK 16 experienced a primary electronics failure on this dive.

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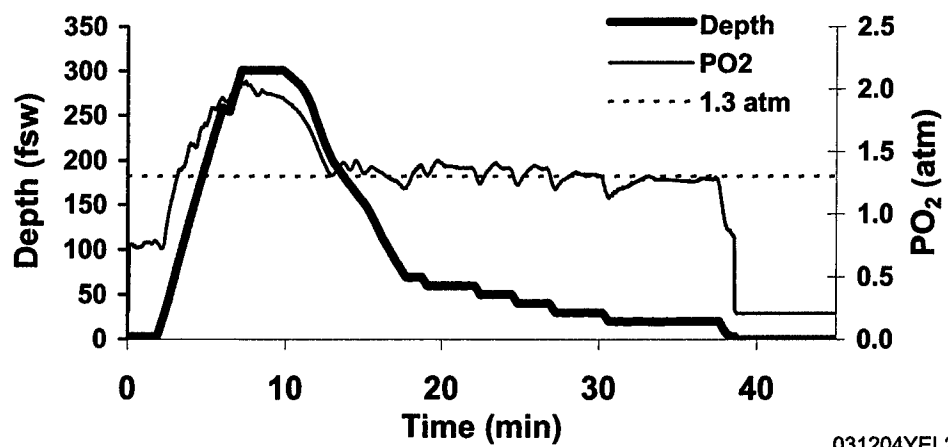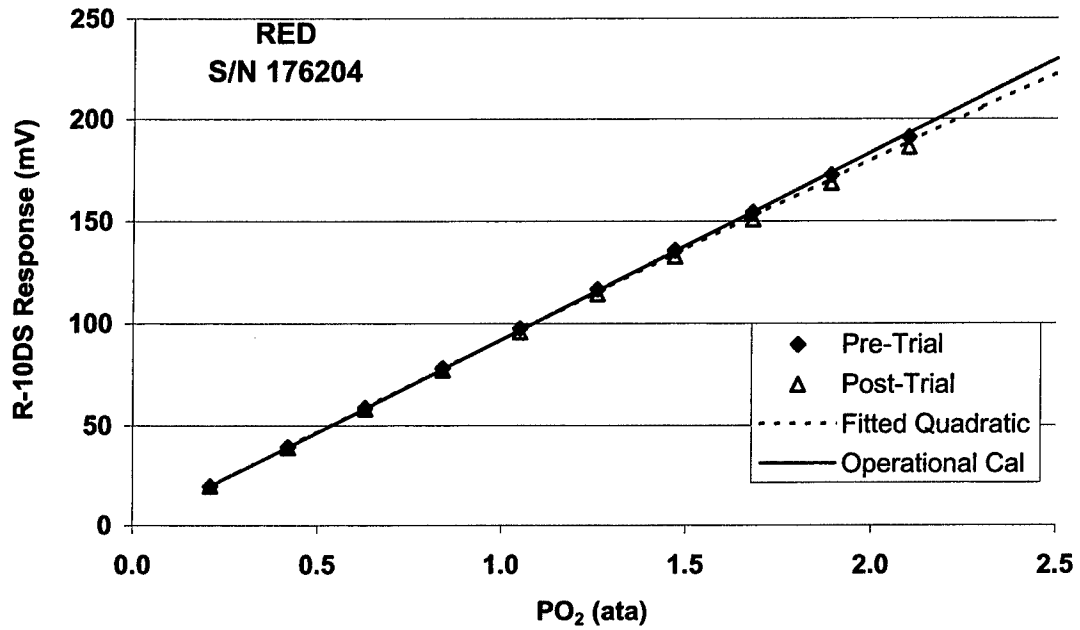031204RED1

031204RED2

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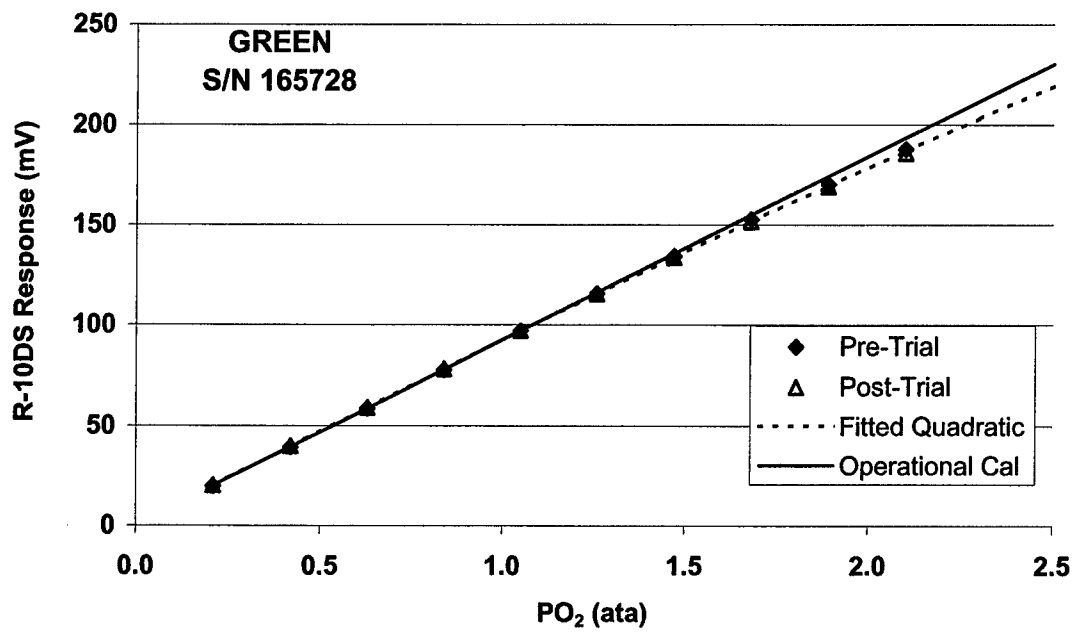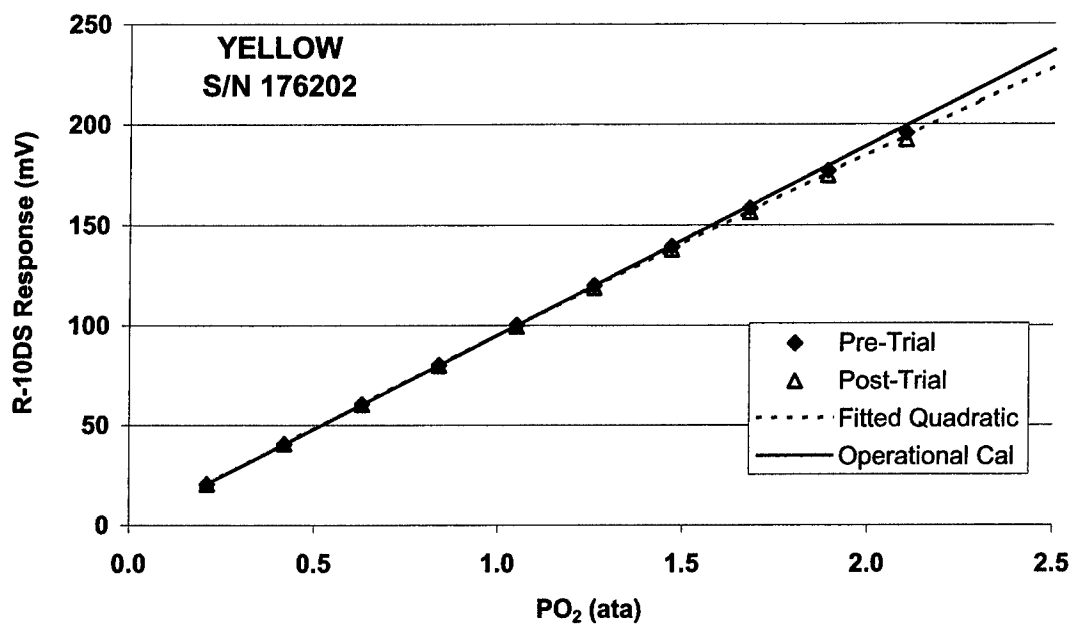031204YEL2

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APPENDIX B

## R-10DS OXYGEN FUEL CELL CALIBRATION CURVES

Fitted Quadratic Coefficients (S/N 176204)	
$V(mV) = \beta_0^L + \beta_1^L P_{O_2}^A + \beta_2^L \left(P_{O_2}^A \right)^2$	
β_0^L	0.04579
β_1^L	94.04947
β_2^L	−2.00975

GREEN
S/N 165728

Fitted Quadratic Coefficients (S/N 165728) $$V(mV) = \beta_0^L + \beta_1^L P_{O_2}^A + \beta_2^L \left(P_{O_2}^A\right)^2$$	
β_0^L	−0.06983
β_1^L	95.63481
β_2^L	−3.13971

B2

YELLOW
S/N 176202

R-10DS Response (mV) vs PO$_2$ (ata)

Legend:
- ◆ Pre-Trial
- △ Post-Trial
- ···· Fitted Quadratic
- — Operational Cal

Fitted Quadratic Coefficients (S/N 176202)	
$V(mV) = \beta_0^L + \beta_1^L P_{O_2}^A + \beta_2^L \left(P_{O_2}^A\right)^2$	
β_0^L	−0.08709
β_1^L	97.98292
β_2^L	−2.63398
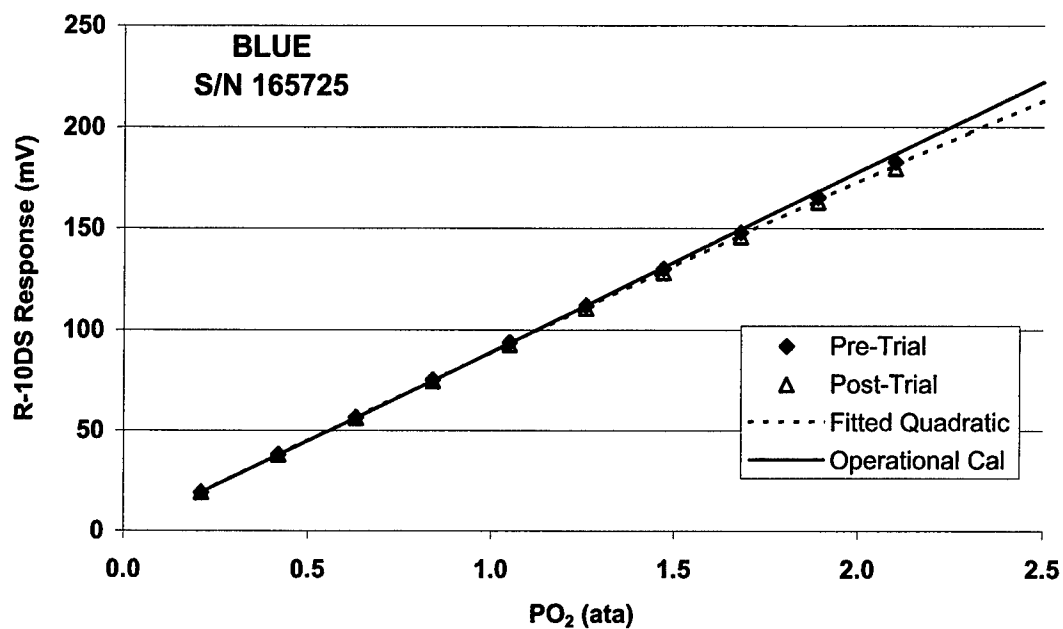
Fitted Quadratic Coefficients (S/N 165725) $V(mV) = \beta_0^L + \beta_1^L P_{O_2}^A + \beta_2^L \left(P_{O_2}^A\right)^2$	
β_0^L	0.10042
β_1^L	91.17955
β_2^L	−2.37185